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NASA Unmanned Flight Anomaly Report:

INVESTIGATION OF ENVIRONMENTALLY-INDUCED ANOMALIES ABOARD JPL SPACECRAFT

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National Aeronautics and
Space Administration

Jet Propulsion Laboratory
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FOREWORD

This document was prepared by the Reliability Engineering Section of the Jet Propulsion Laboratory's Office of Engineering and Mission Assurance (OEMA) to describe recent results and progress of a Flight Anomaly Characterization (FAC) research task. It represents one of a series of analyses of in-flight hardware anomalies which have occurred on Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC), and U.S. Air Force unmanned space programs. Funded by NASA Code QT under Research Technology Operation Plan (RTOP) 623-63-03, entitled *Flight Anomaly Characterization*, their objective is to search for meaningful characterizations of in-flight anomaly data relating to trends, patterns, or similarities that can be exploited to improve product assurance programs. Such improvements may ultimately lead to reduced numbers of anomalies on future unmanned flight programs.

For further information on the content of this report, contact Steve Cornford at (818) 354-1701.

ABSTRACT

This NASA Unmanned Flight Anomaly Report analyzes in-flight anomalies related to environmental conditions encountered on Jet Propulsion Laboratory (JPL) unmanned spaceflight programs. JPL interplanetary spacecraft must endure greater environmental extremes than Earth orbiters. Their design must withstand the temperature variations, radiation, contamination, shock and vibration, electrostatic discharge (ESD), and electro-magnetic interference (EMI) of extended deep space missions. Environmental failures tend to pose a major mission risk; mitigation is dependent on accurate modeling of the environment to be encountered on the mission, proper specification of environmental requirements, adequate design margins, and rigorous testing.

The objective of this analysis was to:

1. Determine whether the in-flight anomaly history reveals identifiable failure modes and trends which represent a risk to future unmanned missions.
2. Identify product assurance process improvements to reduce mission risk.

The report identifies patterns of hardware anomalies due to spacecraft sensitivity to environmental conditions encountered during the mission. The impact of these failures on the respective missions was significant in most cases.

The report recommends product assurance improvements involving refinements in environmental models, requirements specification, design margins, and test, including:

1. Develop improved tools for integrating thermal analysis with 3-D modeling of spacecraft structures.
2. Increase product assurance scrutiny of electronics packaging.
3. Review shock and vibration test sequences, EMI test methods, outgassing & contamination of materials, and potential for transient-induced state changes.
4. Improve sensor technology: develop an integrated suite of miniaturized sensors with a single spacecraft data/command interface.

REFERENCE: (1) *Development of a Method for Flight Anomaly Characterization*, JPL document D-11382, dated January 1994.

I. INTRODUCTION

Scope

This NASA Unmanned Flight Anomaly Report presents the findings of an analysis of in-flight anomalies involving spacecraft hardware susceptibility to environmental damage. The investigation is limited to the JPL Viking, Voyager, Magellan, and Galileo missions, as well as JPL instruments flown on non-JPL spacecraft, where documented in the JPL Payload Flight Anomaly Database (PFAD). Maintained by the JPL Reliability Engineering Section, this database presently includes over 5000 in-flight anomaly reports.

PFAD also includes anomalies reported by Goddard Space Flight Center (GSFC) and the U.S. Air Force. However, these agencies' flight programs were not analyzed in this report due to the lack of detailed information on environmentally-induced anomalies. Major JPL flight programs prior to Viking were excluded from study because of the degree of hardware obsolescence-- conclusions drawn from the flight behavior of early 1960s era hardware are not clearly applicable to current and future JPL reliability programs. Where recent JPL programs, such as Topex, are not discussed, it is because they experienced no discernable in-flight environmentally-induced anomalies or the anomalies were not documented in the problem/failure reporting system.

This report is one product of the Flight Anomaly Characterization (FAC) study, funded under NASA RTOP 323-63-02.

Definitions/Limitations

An "environmentally-induced anomaly" is defined as an incident in which an in-flight spacecraft hardware problem is believed to have been induced by environmental factors, such as shock/vibration, radiation, contamination, thermal control, electro-static discharge (ESD), or electro-magnetic interference (EMI). Telemetry indications of anomalous environmental conditions which were not perceived as posing a real or potential threat to hardware are outside the scope of this study, as are other incidents which JPL did not target for analysis and disposition.

Purpose

This study is one of a series of Unmanned Flight Anomaly Reports funded by NASA Code QT to document investigations of in-flight spacecraft and instrument anomaly data. The results are principally directed toward recommending product assurance process improvements which would lead to a reduced level of risk for future unmanned space missions.

Method

Reference (1) suggests a two-step methodology for grouping and analyzing sets of in-flight spacecraft anomalies with common characteristics, allowing identification of product assurance implications for future programs. In that document, a flow diagram was prepared showing pertinent data from each in-flight anomaly report on JPL spacecraft in the PFAD. After the anomalies were arranged by spacecraft and subassembly, those that appeared related were designated as a group for further analysis. A second flow diagram (see Figure 1) is prepared for each candidate grouping of anomalies with possible product assurance program significance; anomalies related to environmental factors was identified as one of these groupings. This second diagram is further analyzed to validate the suspected correlations (identified by "cross-links" in Figure 1), and to identify any product assurance program implications.

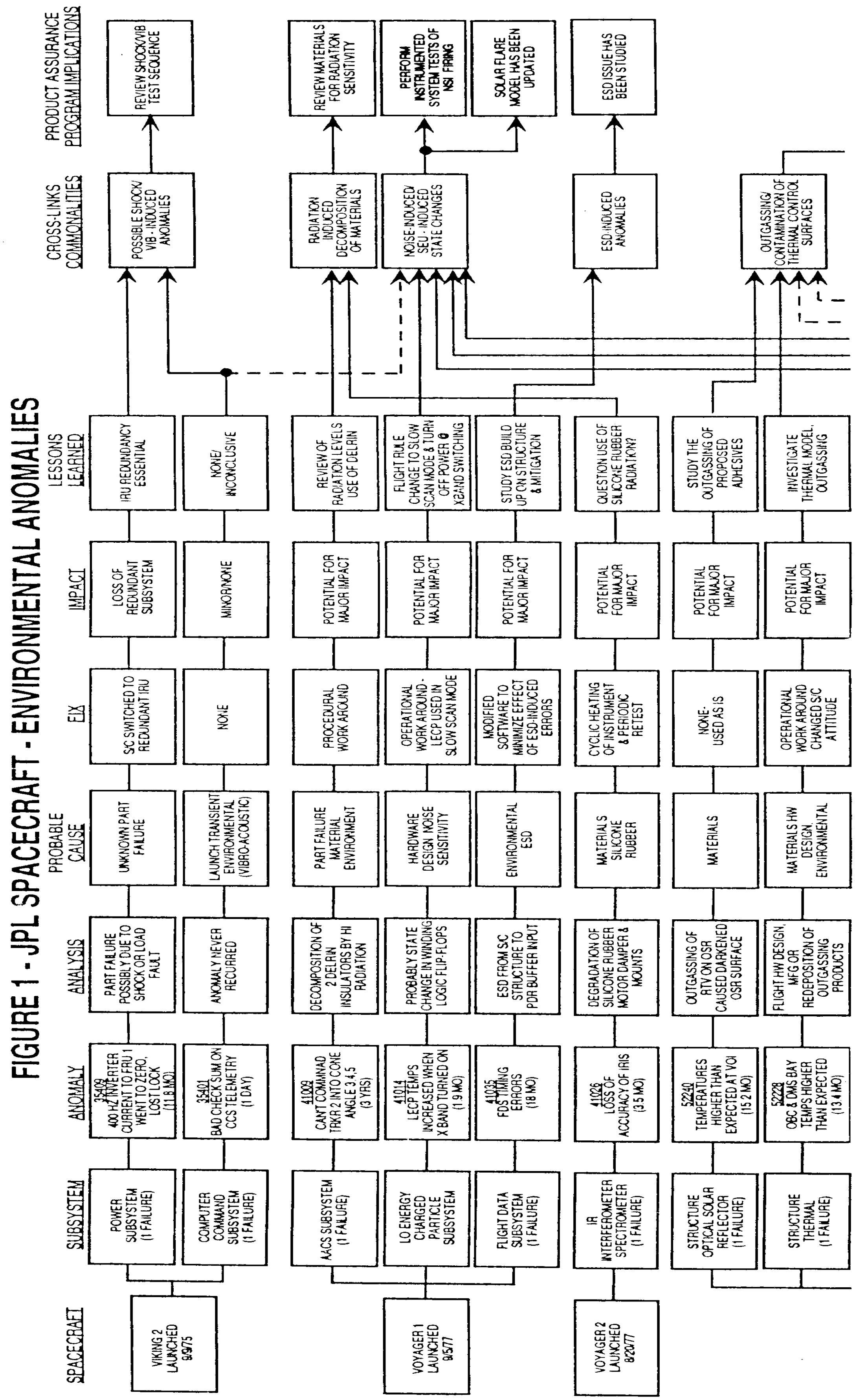
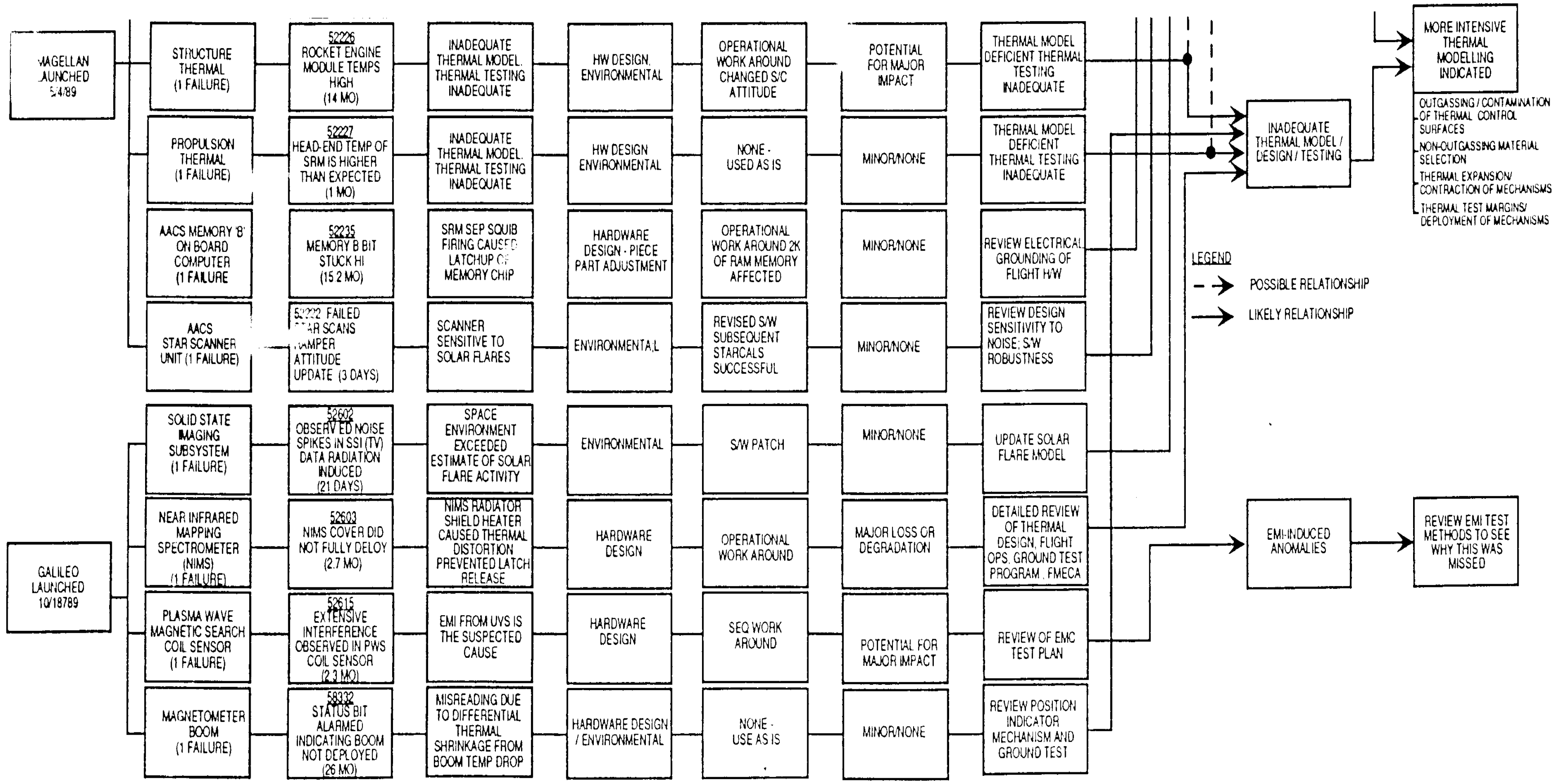


Figure 1 is continued on the next page.



MAGELLAN LAUNCHED 5/4/89
STRUCTURE THERMAL (1 FAILURE)
52226 ROCKET ENGINE MODULE TEMPS HIGH (14 MO)
INADEQUATE THERMAL MODEL. THERMAL TESTING INADEQUATE
HW DESIGN. ENVIRONMENTAL
OPERATIONAL WORK AROUND CHANGED S/C ATTITUDE
POTENTIAL FOR MAJOR IMPACT
THERMAL MODEL DEFICIENT THERMAL TESTING INADEQUATE
PROPULSION THERMAL (1 FAILURE)
52227 HEAD-END TEMP OF SRM IS HIGHER THAN EXPECTED (1 MO)
INADEQUATE THERMAL MODEL. THERMAL TESTING INADEQUATE
HW DESIGN ENVIRONMENTAL
NONE - USED AS IS
MINOR/NONE
THERMAL MODEL DEFICIENT THERMAL TESTING INADEQUATE
AACS MEMORY 'B' ON BOARD COMPUTER (1 FAILURE
52235 MEMORY B BIT STUCK HI (15.2 MO)
SRM SEP SQUIB FIRING CAUSED LATCHUP OF MEMORY CHIP
HARDWARE DESIGN - PIECE PART ADJUSTMENT
OPERATIONAL WORK AROUND 2K OF RAM MEMORY AFFECTED
MINOR/NONE
REVIEW ELECTRICAL GROUNDING OF FLIGHT H/W
AACS STAR SCANNER UNIT (1 FAILURE)
FAILED ATTITUDE UPDATE (3 DAYS)
SCANNER SENSITIVE TO SOLAR FLARES
ENVIRONMENTAL
REVISED S/W SUBSEQUENT STARCALS SUCCESSFUL
MINOR/NONE
REVIEW DESIGN SENSITIVITY TO NOISE; S/W ROBUSTNESS
GALILEO LAUNCHED 10/18/89
SOLID STATE IMAGING SUBSYSTEM (1 FAILURE)
52602 OBSERVED NOISE SPIKES IN SSI (TV) DATA RADIATION INDUCED (21 DAYS)
SPACE ENVIRONMENT EXCEEDED ESTIMATE OF SOLAR FLARE ACTIVITY
ENVIRONMENTAL
S/W PATCH
MINOR/NONE
UPDATE SOLAR FLARE MODEL
NEAR INFRARED MAPPING SPECTROMETER (NIMS) (1 FAILURE)
52603 NIMS COVER DID NOT FULLY DELOY (2.7 MO)
NIMS RADIATOR SHIELD HEATER CAUSED THERMAL DISTORTION PREVENTED LATCH RELEASE
HARDWARE DESIGN
OPERATIONAL WORK AROUND
MAJOR LOSS OR DEGRADATION
DETAILED REVIEW OF THERMAL DESIGN, FLIGHT OPS, GROUND TEST PROGRAM, FMECA
PLASMA WAVE MAGNETIC SEARCH COIL SENSOR (1 FAILURE)
52615 EXTENSIVE INTERFERENCE OBSERVED IN PWS COIL SENSOR (2.3 MO)
EMI FROM UVS IS THE SUSPECTED CAUSE
HARDWARE DESIGN
SEQ WORK AROUND
POTENTIAL FOR MAJOR IMPACT
REVIEW OF EMC TEST PLAN
MAGNETOMETER BOOM (1 FAILURE)
58332 STATUS BIT ALARMED INDICATING BOOM NOT DEPLOYED (26 MO)
MISREADING DUE TO DIFFERENTIAL THERMAL SHRINKAGE FROM BOOM TEMP DROP
HARDWARE DESIGN / ENVIRONMENTAL
NONE - USE AS IS
MINOR/NONE
REVIEW POSITION INDICATOR MECHANISM AND GROUND TEST
INADEQUATE THERMAL MODEL / DESIGN / TESTING
MORE INTENSIVE THERMAL MODELLING INDICATED
OUTGASSING / CONTAMINATION OF THERMAL CONTROL SURFACES
NON-OUTGASSING MATERIAL SELECTION
THERMAL EXPANSION/ CONTRACTION OF MECHANISMS
THERMAL TEST MARGINS/ DEPLOYMENT OF MECHANISMS
LEGEND
POSSIBLE RELATIONSHIP
LIKELY RELATIONSHIP
EMI-INDUCED ANOMALIES
REVIEW EMI TEST METHODS TO SEE WHY THIS WAS MISSED

II. DATA ANALYSIS

<u>In-Flight Anomalies: Major JPL Spacecraft Programs</u>

Applying the flow diagram technique to major JPL spacecraft programs, one characteristic pattern that emerged was a number of early to mid-mission anomalies revealing environmental vulnerabilities, including shock/vibration, radiation, contamination, thermal control, electro-static discharge (ESD), and electro-magnetic interference (EMI). The JPL failures are examined in Figure 1. Sixteen in-flight anomalies, including 9 with significant mission impact (rated as "Major Loss or Mission Degradation" or "Potential for Major Impact"), were documented on the Viking, Voyager, Magellan, and Galileo flight programs.

The anomaly characterizations in Figure 1 include the following incidents documented by JPL Problem/Failure Reports (PFRs) where in-flight anomalies were attributed to environmental exposure:

Magellan - PFRs 52240 & 52228. Magellan thermal design requirements were severe. The spacecraft was designed to withstand sunlight about twice as intense as that of Earth, with the temperature of shaded surfaces expected to fall to -204°C. Maneuvers conducted throughout the mission exposed most spacecraft surfaces to repeated temperature extremes. The following in-flight anomalies indicate that thermal design margins constrained performance of the spacecraft extended mission, although they proved adequate for completion of the primary mission. In the absence of backup hardware and operational work-arounds, however, the primary mission would likely have been lost or seriously degraded.

During Venus encounter, temperatures in the Magellan electronics bays exceeded Venus orbit insertion (VOI) predictions and bay acceptance limits (PFR 52240). Beginning early in the mission, sensor readings in the onboard computer (OBC) bay area (PFR 52228) and the command data subsystem (CDS) bay indicated higher than expected temperatures throughout the spacecraft bus. JPL attention focused on the 1" x ½" Optical Solar Reflector (OSR) tiles which control solar absorption by the Magellan spacecraft bus. Degraded reflectance of these tiles appeared to be the best explanation of the problem, since no defects could be found with the thermal model nor the solar thermal vacuum test data. Electronics bay temperatures were greater than predicted from early cruise, through Venus orbit insertion and mapping. Since the new OSR absorptance curve could affect flight operations, including limiting data collection during certain Venus mapping cycles, the mission impact was rated as "Potential for Major Impact."

The most likely cause for degradation of the OSRs is contamination of the reflective surface by spacecraft materials which affect heat absorptance. Major contributors to the contamination were the RTV adhesive used to attach the OSRs to the spacecraft and the structural adhesive used in the solar panel honeycomb. Organic products from this glue may have outgassed when exposed to vacuum, and studies showed that the intense exposure to ultraviolet light may have caused them to polymerize on the OSR surface and reduced its reflectance. Although Magellan thermal-vacuum tests did not reveal this problem, longer duration high temperature tests conducted by the Topex project on qualification panels using a similar honeycomb material detected significant venting from the edges of the panels. During aerobraking in the upper atmosphere of Venus, atomic oxygen apparently cleaned the tile surface, lending credence to the "increased absorptance due to polymerization" hypothesis.

The effects of Magellan's diminished thermal control were experienced mainly during portions of orbit representing thermally severe intervals. During these intervals, science objectives were met through the use of other thermal control options. For example, "go hide"-- attitude adjustments which positioned the bulk of the spacecraft in the shadow of the high gain antenna-- proved effective. However, mapping was not possible during the 10 minutes of "go hide" on alternate revolutions. Of the four temperature limit violations discussed, this OSR-related bus over-temperature problem had the greatest impact.

The thermal control problems did not thwart Magellan's primary mission. Total planetary coverage reached 98 percent, as compared to a mission objective to map 70 percent. Despite the temperature extremes encountered, the thermal subsystem provided sufficient margins for thermal control measures by flight operations to be effective. However, the anomalies had a significant impact on the Magellan extended mission. "Go hide" mapping interruptions caused missed opportunities to obtain data at different angles of observation, which would have enhanced the primary mission data. Redundant observations produced significantly less overlap of data at different angles than had been expected by mission planners.

The Magellan ground test design was fortuitous. Since system thermal-vacuum test at an internal spacecraft temperature of 20-25^{0}C would not achieve the anticipated increase from <0.10 absorptance at beginning-of-life (BOL) to 0.16 at the end of the mission, test planners elected to add extra internal heaters and test at 50^{0}C. Due to the OSR contamination, an absorptance of 0.32 was observed at end-of-life (EOL)-- twice the anticipated value. Because the spacecraft had been tested at 50^{0}C, mission operations had the confidence to operate Magellan at the higher temperatures resulting from the increased absorptance.

<u>Lessons Learned</u>: *Include a "hot margin" phase in system thermal-vacuum test to demonstrate spacecraft operation at temperatures greater than worst case design predictions. Consider requiring vacuum bakeout of all organic adhesives, especially structural. Update the optical properties database to include the Magellan experience, and supply BOL/EOL thermal property data for NASA-wide use. Adequate thermal margins reduce mission risk. Ground control of spacecraft provides opportunities for implementing operational work-around solutions.*

Magellan - PFR 52226. Shortly after launch, telemetry indicated that Rocket Engine Module (REM) temperatures were higher than predicted. In a tail-towards-sun attitude, REM temperatures ranging from 39^0 to 51^{0}C were detected, instead of the 15^0 to 25^{0}C expected. The direct operational impact of this anomaly was to impose attitude constraints on a certain portion of the cruise phase of the mission, as well as during mapping of the Venusian surface. Mission planners had to maintain spacecraft attitudes which would preclude pointing the rocket engine nozzles towards the sun. This precluded mapping of higher planetary latitudes during the first extended mapping mission, and it resulted in some loss of extended mission data.

The anomaly was probably caused by an error in simulating the thermal environment and setting appropriate requirements for the spacecraft thermal subsystem. The mathematical thermal modeling of the REM had been delegated to a vendor. During system thermal-vacuum test, a high temperature reading was observed from the solar simulation. The vendor implemented a corrective action (a sleeve around the 100 Lbf catalytic bed regions), but the schedule did not allow for test verification. Insolation of the interior of the rocket nozzle in a tail-towards-sun spacecraft orientation (nozzle entrapment) could not be simulated with the existing test fixture, and a low emittance nozzle coating impeded heat transfer. Improved automated tools are needed which would integrate thermal analysis with three-dimensional modeling of spacecraft structures. This would facilitate thermal analysis and provide a clearer picture of the effect of design measures on the thermal budget in varying thermal environments.

Lessons Learned: Avoid delegating responsibility for thermal control design: it should be retained by the spacecraft prime contractor. Verify thermal control design changes by test. Perform solar thermal-vacuum test at the subsystem level; or if subsystem testing is not performed, system solar thermal-vacuum test should simulate several attitudes for the subsystem. Consider use of improved automated tools for integrating thermal analysis with three-dimensional modeling of spacecraft structures. Adequate thermal margins minimize mission risk.

Magellan PFR 52227. One month after the REM over-temperature problem was reported (PFR 52226), the temperature of the solid rocket motor (SRM) forward flange area was also found to be higher than expected. Thermal analysis indicated that the effective solar absorptance of the separation flanges was underestimated.[1] Model correlation showed that the absorptance was approximately 0.53 instead of 0.36. This additional heat transfer could be explained by an increase in the solar absorptance of the separation flanges above the value assumed by the Magellan TRASYS model. The specific design factors contributing to the discrepancy could have included cavity effects from the ⅝" separation bolts, improper anodization of the exposed separation flanges, or additional heat input from uncovered electrical connectors. Subsequent test showed that the resulting higher temperatures were within the acceptable range, and that no operational solutions such as attitude adjustments were necessary. Hence, this temperature limit violation had no impact on the primary nor the extended mission.

Lessons Learned: Require a positive inspection to confirm that anodic coatings are present on bare surfaces that require them for thermal control, and verify the emittance of the coating with a portable emissometer. Adequate thermal margins minimize mission risk. Update the thermal models when discrepancies are discovered.

Magellan - PFR 52235. Within 7 seconds after solid rocket motor separation, the B-side of the Magellan command data subsystem (CDS-B) received erroneous alert codes from AACS-B. This anomaly was isolated to memory B in the on-board computer, where memory bit 4 was found to have stuck high, causing the CDS to address memory location 6211 instead of 6201. This addressing failure affected at least 2K of RAM. Memory B was marked off-line to inhibit read/writes to memory B, preventing the AACS from operating in memory B RAM and causing an inadvertent command to be accepted by the AACS. JPL was able to match these symptoms using a failure model in which a latch up failure occurred to a TCC244 chip.

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[1] Esterl, G.: Memo 92-MGN-12-036, informal Jet Propulsion Laboratory memorandum, August 27, 1992.

A voltage transient through the spacecraft chassis is the suspected cause of the memory failure. JPL determined through ground tests that by firing one or more NSI (NASA standard initiator) devices, a plasma path to the case could conduct enough chassis current to cause the memory failure. Chassis current can be generated when the NSI conductors short to case during their firing; eight NSIs were used simultaneously during SRM separation. The AACS memory board is physically located ¼-inch above the ground plane, and a voltage transient of only one volt is sufficient to cause the AACS memory B failure. The results of NSI ground test firings led to the conclusion that a memory failure could result from this noise-induced environment, and a TCC244 latch up model prediction of eventual "self-healing" corresponded to observations.

Magellan was equipped with two redundant AACSs, including two 32K memories and two processors-- all cross-strapped to be interchangeable. When the memory loss occurred, memory B was serving as a backup, performing the same functions as memory A but not controlling the spacecraft. Although some areas of memory could not be examined from the ground, it appears likely that 4-8K of memory B became unreliable and, in effect, unavailable for use. If this loss of available memory space had occurred permanently in memory A and the spacecraft had had no redundant B-side, the mission would have ended at SRM separation. If this intermittent condition had occurred later in a single-string mission, ground controllers might have been able to program around the glitch. Their success would have depended on which particular code was in the affected memory space at the time of the failure and whether the programmers had time to insert a fix before the mission entered a critical phase.

<u>Lessons Learned</u>: *Since this incident, work has begun on an improved grounding standard. Review the electrical grounding of flight hardware and the potential for noise-induced state changes. Perform instrumented system tests of NSI firing to investigate the potential for noise-induced failures. Standard circuit analysis methods do not consider vulnerabilities which are not represented on schematic diagrams, such as circuit board proximity to ground plane. Hardware redundancy (with physical separation of units has benefit in assuring spacecraft survival in noise environments.*

Magellan - PFR 52222. The Magellan star scanner unit (STU) provides attitude updates to the AACS by acquiring two, known location, reference stars within its field of view (FOV). Beginning with the first star calibrations (starcals) attempted after launch, the STU began to generate unsuccessful starcals, hampering the spacecraft attitude update process. Review of star scan data suggested that the scanner signal was being prompted by a stimulus other than the target stars. This interference caused the starcal sequence to reject the correct star data, resulting in no attitude update; at other times, the false data was accepted, producing an incorrect attitude update. Starcal No. 1 rejected the first reference star and missed the second star, No. 2 misread the magnitudes of both stars, and No. 3 found both stars but rejected the first.

Analysis centered on the Starcal No. 3 failure. For each starcal in a series, the STU alternates between a forward scan (Swath 1) and a reverse scan (Swath 2). No. 3 was performed on the reverse scan sweep. Real time memory readout (MRO) analysis showed that the first star registered was the correct first target star (Gamma Crux), but that it was rejected because of a possible STU idiosyncrasy. It was postulated that because the reverse scan (Swath 2) caused the STU FOV to sweep across the Milky Way before reaching the target star, the background voltage buildup from first viewing the dense star field caused a misreading of Gamma Crux.

This explanation was later rejected when data received over the following 25 days showed that the next thirteen Swath 2 starcals were successful (with the exception of a single, unrelated failure). With the subsequent thirteen Swath 1 scans also successful, a random hardware failure within the STU also appeared unlikely. Further analysis led to a second preliminary conclusion that a stray particle or object became lodged in the STU FOV, possibly as a result of launch or near-earth activities, such as inertial upper stage (IUS) separation.

This problem afflicted Magellan for over a year. After contacting the vendor, JPL discovered that the star scanner was known to be sensitive to stray light. JPL implemented a continuing software fix, implementing a set of foreground and background software filters for the AACS star recognition process. An additional software filter was added to correct for astro-quartz particles flaking off the outside of thermal blankets during the transition from sun to shade. Qualified for the first time on Magellan, curing and outgassing processes may have left a brittle blanket surface. Maneuvers were also revised to minimize thermal cycling of the blankets near the scanner during starcals. Although the logic screening filtered out most of the spurious proton inputs, occasional problems recurred during solar flares-- this year represented a peak in solar flare activity. The mission impact was considered minor, causing some swaths of missing data and some mistakes in correlation of the radiometric data with the radar data.

Lessons Learned: Review design sensitivity to contamination, spurious signal noise, and software robustness. Since this incident, the solar flare model has been updated.

Galileo - PFR 52603. A command was issued to jettison the instrument optics cover and radiative cooler cover from the Galileo Near Infrared Mapping Spectrometer (NIMS). The two covers were designed to be unlatched simultaneously by a pair of lanyards operated by a pyro-actuated release mechanism. The subsequent absence of the expected cooling trend for the Focal Plane Assembly (FPA) was interpreted as a failure of the cooler cover to fully eject. This obstruction would have prevented operation of the instrument and caused major mission degradation.

After de-energizing the NIMS cooler shield heater, the FPA temperature plunged, and it continued to drop at the nominal "cover gone" rate after the shield heater was re-energized. The nominal temperature was achieved, indicating full cover deployment.

The anomaly was attributed to a flight rule violation. Failure investigation concluded that heating of the cooler shield by the shield heater caused excessive thermal distortion of the cover and shield, preloading the spring-driven latch pin and preventing cover release. Energizing the 30- watt shield heater prior to cover ejection was an add-on flight sequence intended to drive contaminants from the radiator shield. This concern about contamination arose years after the hardware had been qualified. The shield heater had never been activated during cover deployment thermal/vacuum tests, and hardware designers were not informed of the change in planned sequence.

The design was sufficiently robust that the unplanned sequence caused no permanent damage.

However, the command to turn off the heater was sent as part of the anomaly investigation. Had the spacecraft possessed greater autonomy from ground control, it is unlikely that onboard programming would have initiated this corrective action.

JPL has always conducted a formal review of deployment sequences. Following this flight rule violation, however, JPL instituted an additional Deployment Review requirement. This special review is held for each in-flight deployment, such as a shade retract, and is intended to ensure that flight operations do not violate design limitations.

<u>Lessons Learned</u>: *"Fly it like you test it:" Operations should obtain concurrence from thermal designers before commanding environmental changes to the mission profile. JPL now requires a Deployment Review prior to every commanded deployment. Adequate thermal margins minimize mission risk. Contamination concerns should be addressed early in the hardware build cycle.*

Galileo - PFR 52615. The Galileo Plasma Wave Spectrometer (PWS) is an instrument for studying electromagnetic waves and wave-particle interactions. During cruise, extensive interference was observed in the PWS magnetic search coil sensor. The suspected cause of the interference was (1) spin bearing noise, and (2) EMI produced by the Ultraviolet Spectrometer (UVS) stepping motor. This anomaly had a potential for a significant impact on instrument performance.

A very sensitive magnetic field detector, the PWS instrument detected harmonics produced by the stepper motor, located at the end of the magnetometer boom and on the scan platform, respectively. The occurrence of this problem is dependent on the location of the motor and on the harmonic frequencies. Since researchers desire very high sensitivity in science instrument sensors, it is difficult for engineers to design a test configuration which can characterize every background EMI source. More data is needed to enable JPL to accurately predict the actual flight environment.

The interference problem was minimized by operational measures to segregate instrument operation in the various modes.

<u>Lessons Learned</u>: *Analyze ground test variances from the flight environment.*

Galileo - PFR 52602. Three weeks after launch, noise spikes were observed on Solid State Imaging Subsystem (SSI) frames. Occurring at a rate of about ten per second, they appeared characteristic of radiation induced events. Analysis of SSI science indicated a likely correlation with the high solar activity. This sensitivity to radiation-induced noise was reduced by a software patch to a minical sequence.[2]

The radiation environment for the Galileo mission substantially exceeded the estimate of solar flare activity. During the same time period, these conditions also affected Magellan performance (see PFR 52222). The impact of this anomaly on the mission was very minor; however, the subsequent update of the solar flare model may permit future systems to be designed to more realistic radiation requirements.

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[2] A *minical* is a coarse calibration based on a limited number of data points.

The SSI instrument design was sensitive to radiation induced events. As with the PWS incident described above (PFR 52615), noise control is problematic where payloads include sensitive instruments. Since we cannot capture the flight environment in the ground test of instruments-- including the presence of radioisotopic thermal generators (RTGs), solar flares, and trapped planetary environments-- additional data and analysis on environmental conditions are needed.

Lessons Learned: *Perform further characterization of the flight environment, including radiation induced events. The solar flare model has now been updated.*

Galileo - PFR 58332. A microswitch on the Galileo Magnetometer Boom sends a signal when the collapsible boom becomes fully deployed. About two years into the Galileo mission, the signal changed to an indication that the boom was not deployed. However, all other spacecraft indications suggested that the boom was deployed.

Attached to the Mag Boom is a beryllium-copper deployment lanyard, which is fed out by a rate limiter to control the speed of boom self-erection during deployment. Normally slack after deployment, thermal shrinkage of the lanyard is believed to have rotated the microswitch bracket about its mounting screws. Ground tests confirmed that lanyard shrinkage (caused by a drop in the temperature of the fiberglass boom structure) would deactivate the switch.

The impact of this anomaly was minor since the boom was deployed and fully operational.

Lessons Learned: *Review thermal expansion effects in establishing the design margin for the position indicator mechanism, and review ground test requirements. Develop improved product assurance approaches for qualifying deployable mechanisms.*

Voyager 1 - PFR 41035. During the Voyager 1 encounter with Jupiter, an excessive offset between the command and control subsystem (CCS) and the flight data subsystem (FDS) clocks was observed, resulting in the loss or degradation of key science data. The CCS clock provides an hours pulse which is keyed to the timing of FDS frame starts, serving as a reference for sequential events such as scan platform positioning. If the hours pulse occurs too soon relative to FDS frame starts, there is a loss of event timing synchronization necessary for proper execution of data collection sequences. The anomaly was rated as having "Potential for Major Impact."
Instead of occurring immediately after a frame start, data showed that the CCS hours pulse was occurring eight seconds prior to it. This resulted in a number of anomalous incidents reflecting loss of FDS frame synchronization with the inertial sensor subassembly (ISS), FDS data mode changes, etc. Examination of spacecraft real time data revealed that 40 power-on resets (PORs) of the FDS had occurred over the same time period as a dramatic increase in timing offset. Since each FDS POR is set to delay FDS time by 200 milliseconds, the 40 PORs account for the eight second offset between the two independent clocks.

PORs are initiated by a logic circuit in the FDS processor. Tests showed that spurious signals could be induced into the FDS processor POR input buffer which would enable the 200 millisecond delay logic. Furthermore, they showed that a pulse produced by an electrostatic discharge would be consistent with such a signal. JPL analysts concluded that the source of the interfering signals was electrostatic discharges originating on the external surface of the spacecraft and conducted through a cable harness to spacecraft ground. However, electrostatic discharges are capable of generating 10 to 100 times the current demonstrated as triggering the POR logic. If the PORs were caused by electrostatic discharge, it is odd that no similar anomalies were reported for Voyager 2 during its Jupiter encounter.

The offset was corrected through real time commands sent to delay the CCS hour pulse, re-synchronizing the CCS with the FDS frame start. To prevent a reoccurrence, a software procedure was provided for automatically re-synchronizing the CCS with the FDS during sequence execution. For future FDS design, transient suppressors were recommended for installation on lines connecting modules vulnerable to logic latches.

<u>Lessons Learned</u>: *Since this incident, mitigation of ESD charging on spacecraft structures has been studied. Consider use of transient suppressors on sensitive module interconnections.*

Voyager 1 - PFR 41014. Low Energy Charged Particle (LECP) subsystem temperatures increased about two months into the mission. The largest increase was in motor temperature, which changed from 4^0 to 53.5^0C. The temperature increase appears to be coincident with powering of the X-Band transmitter.

Analysis of anomaly data traced the problem to the switch in the motor step logic circuit (Figure 2). Pulsed open and closed in normal motor stepping operation, the switch stuck in the closed position for the duration of the high temperature anomaly. This allowed the motor winding in series with the logic circuit to draw about 7 watts continuously for 18 hours. Since switch S-1 is closed in the "accelerated motor step rate" mode of operation, the excess power would have overloaded and damaged the 150 ohm, ½ watt resistor in series with S-1. Dissipation of the excess power by the circuit was viewed as a likely cause of the observed temperature rise in the instrument. Since the anomaly was coincident with X-band transmitter powering, it is likely that a power transient associated with that event effected a state change in the logic. Tests conducted to simulate power dissipation through the ½ watt carbon composition resistor resulted in a significant reduction in the resistance value of the part.

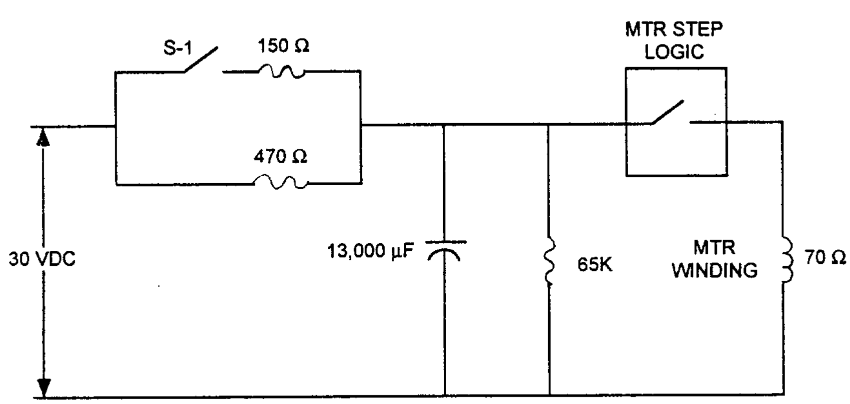

Figure 2
Simplified LECP Motor Stepping Circuit

The prospect of lowered resistance in the motor stepping circuit raised concern about excessive current flow in the accelerated stepping mode. The anomaly is rated as "Potential for Major Impact." Circuit analysis shows that the resistance change would not affect LECP operation in the slow scanning mode, which restricts step pulsing to once every 48 seconds. To prevent damage to the instrument, JPL provided a software patch which keeps switch S-1 in the open position, proscribing future use of the accelerated mode. Corrective action also included generation of a safing sequence to turn LECP motor power off during all X-band power changes. With these remedies in place, the instrument completed its mission successfully.

Lessons Learned: Evaluate potential for noise-induced state changes, e.g., transmitter powering.

Voyager 1 - PFR 41009. The Canopus Star Tracker (CST) utilizes Canopus or another reference star for attitude control during spacecraft maneuvers. As the spacecraft rotates about its Z axis (rolls), the CST generates error signals when the light source focused on the light sensor diverges from the "roll" centerline of the sensor's field of view. A high signal-to-noise ratio is obtained by scanning only discrete areas, designated as cone angles C1 through C8, of the light sensor, an image dissector tube. The Attitude and Articulation Control Subsystem (AACS) commands an electrostatic deflection system to switch to one of the preset cone angles to sense an appropriate reference star. Voyager carries both a primary and a backup CST.

The primary CST (CST2) began to exhibit degraded performance during Jupiter encounter. The cone angle position readout telemetry indicated discrepancies between certain commanded cone angles and the actual cone angle achieved by the CST. In addition, a degraded roll error signal was detected in certain cone angles, traced to incorrect voltages on the cone angle deflection plates. Substitution of inoperable cone angle C4 with the adjacent C8 would have seen the spacecraft through Saturn encounter, but any further degradation in the roll error signal could have affected post-Saturn spacecraft guidance. The anomaly was rated as having "Potential for Major Impact." The most probable cause of the CST anomaly is the failure of a high voltage SDT 5553 transistor which drives the cone angle deflection plates. Test showed that this failure mode could be attributed to either base-to-emitter or collector-to-emitter leakage in the transistor. The transistor is located in a tungsten box for radiation shielding, and the probable cause of the leakage is failure of the Delrin sleeves which insulate the transistor leads where they enter the box. Analysis indicated that Delrin decomposes when exposed to radiation, and that the box was susceptible to electrostatic charging. An electrostatic discharge from the ungrounded tungsten box could carbonize a path through the defective sleeves, producing a high resistance leakage path between the SDT 5553 leads and causing the transistor to appear almost saturated all of the time.

The lack of similar symptoms in the CSTs aboard Voyager 2 has been attributed to the higher radiation flux aboard Voyager 1, which flew much closer to Jupiter. No corrective action was feasible for restoration of the CST position command function, although a work-around solution enabled the primary tracker for the cone ranges needed for the next planetary encounter. Use of the backup CST was not necessary, and annealing led to eventual recovery from the degraded CST performance. The failure investigators recommended against the use of Delrin insulating sleeves in future applications, and in favor of grounding all metal shielding boxes including those located inside equipment housings.

Lessons Learned: Review the electrical grounding of flight hardware. Review materials for radiation sensitivity. Incorporate radiation induced behavior into worst case analyses.

Voyager 2 - PFR 41026. Three and one half months after Voyager 2 launch, degraded sensitivity of the Infrared Interferometer Spectrometer (IRIS) was discovered during data analysis at GSFC. The noise equivalent radiance (NER) of the instrument was observed to have increased from 100 to 300 units. The NER increase was verified by test. Uncorrected, the mission impact of the degraded signal would be reduced spectrometer responsiveness in the long wavelengths, increased susceptibility to scan platform vibration, and reduced safety margin in control of the IR interferometer. The effect on the mission was rated as "Potential for Major Impact."

Correction of this problem was needed in time for Jupiter encounter. Real time analysis and corrective action did not occur because the problem was not discovered until experiment data record (EDR) analysis was performed by the Principal Investigator. Subsequent failure analysis attributed the degraded instrument performance to mirror deformation from phase separation and crystallization of the silicone rubber in the motor damper and beamsplitter mounts.

The IRIS flash-off heater was used to generate warming cycles to reverse the material crystallization. The spectrometer was warmed for 20 hours and then allowed to cool before powering the instrument. This one-time corrective action resulted in a dramatic improvement in signal magnitude, and it essentially rehabilitated the instrument. The timing of the heater use during cruise phase was opportune in that it permitted time for thermal stabilization and instrument recalibration prior to planned science observations. Some slight degradation in the infrared sensitivity of the detector resulted from this incident.

Lessons Learned: Review polymer materials for radiation sensitivity in the proposed application; fault tree analyses (FTAs) and failure mode and effects analyses (FMEAs) should reflect such sensitivities. Ground control of spacecraft provides opportunities for identifying in-flight problems and implementing operational work-around solutions.

Viking 2 - PFR 35409. At 26 seconds after separation of the Viking Lander, the current went to zero on the 400 Hz inverter providing power to the inertial reference unit IRU-1, causing the gyro spin motors to run down. A Failure Modes and Effects Analysis was performed, which included simulation of various component failures on the 400 Hz inverter breadboard. The analysis showed that a large number of single component failures could have resulted in loss of gyro power but would not account for the observed power signature. However, failure of two component types-- a collector-to-emitter short on one of the 2N2880 output transistors or a short of one of the protective diodes-- could have caused the observed anomaly. The mission impact of the anomaly was rated as "Loss of Redundant Subsystem."

The fix was accomplished by switching the spacecraft to a redundant IRU. The cause of the postulated component failures remains unknown; possible causes include part damage from mechanical shock, random failure, or electrical conditions induced by a load fault. Given the timing of the anomaly, shock or vibration associated with Viking Lander separation seems a plausible explanation. Recent insights suggest EMI from pyro firing as a likely cause.

Lessons Learned: Hardware redundancy is shown to have benefit in assuring spacecraft survival in extreme environments. Consider designing hardware to prevent ground currents caused by open or short circuits. Review shock and vibration test sequence.

Viking 2 - PFR 35401. Spacecraft onboard computers are programmed to conduct and report frequent readouts of processor memory to check for errors caused by hardware failures, software defects, or interface problems. Shortly after launch of Viking 2, telemetry indicated an erroneous checksum value for Processor B.[3] All other processor readings were nominal. The fault indication was traced to memory location 4416, which registered a checksum of 705200 instead of the correct value of 705227, denoting a data loss. Since the same memory area had been checked at launch minus ten minutes and found to be correct, a launch transient was suspected. Extensive investigation of the Viking flight software failed to pinpoint an actual defect which would explain the checksum error. Tests revealed only one candidate functional single-point failure: a one-bit change which could result in a WAIT instruction appearing as a SENT instruction. This could have been caused by the failure for a few microseconds of a single gate in an instruction register. However, the temporary clearing of the WAIT condition code represented no impact on spacecraft operations, no subsequent checksum errors occurred, and Processor B performed flawlessly before and after the anomaly. The mission impact of the anomaly was rated as "Minor/None."

No corrective action was implemented. JPL concluded that the apparent functional single point failure must have been induced by vibration, pressure change, or EMI in the launch environment. Review of the environmental tests conducted on the Viking command and control subsystem (CCS) revealed that ground test would not detect this specific transient failure mode.

Lessons Learned: Inconclusive. (Potential for mitigation through environmental requirements specification.

In-Flight Anomalies: JPL Science Instruments Aboard Non-JPL Spacecraft

The Figure 1 flow chart includes flight anomaly data on JPL-designed instruments aboard JPL spacecraft. In addition, data has also been obtained on JPL-designed instruments which flew on non-JPL spacecraft. The following data was reviewed to aid in understanding environmentally-induced failure trends.

ASTROS - PFR 53831/55359. The sensor assembly (SA) in the Astro Star Tracker (AST) experienced an uncontrolled and unmonitored cold temperature excursion which exceeded its design limits. This occurred during the preparation of the Ultraviolet/Visible Shuttle Attached Observatory (ASTROS-1) instrument for Shuttle de-orbit. Power to the AST had been turned off as part of payload deactivation, causing a loss of thermal monitoring and control. At this time, the payload was in its stowed position with the sensor electronics at +23°C. Subsequently, the payload bay was positioned in the Shuttle shadow with the Shuttle in a tail-to-Earth orientation for about 2¼ hours, subjecting the equipment to a temperature of -45°C.

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[3]A *checksum* is a value used to ensure that data is transmitted without error. The checksum value is the sum of the binary characters in a block of data. When the data block and checksum value are transmitted, a new checksum is computed at the receiving end. The values are compared, and a non-match indicates an error.

Functional test of the SA upon return to JPL demonstrated proper operation (PFR 53831). Visual inspection of circuit boards, however, revealed damage attributable to the cold temperature excursion-- several cracked solder joints at IC lead pads. Excess solithane coating was removed from the boards and a thin layer reapplied, and the SA passed vibration, thermal/vacuum, and a 500-hour lifetime test. The AST electronics assembly was also tested successfully (PFR 55359), but it was designated as a spare and was not fully inspected for damage.

JPL concluded that the unplanned mission profile and resultant low temperature condition experienced by the ASTRO-1 mission might well be specified as a design requirement in future missions. Formal specification of the required in-flight temperature environment, as well as formal qualification of the instrument in compliance with that temperature environment, should recognize the likelihood of reasonable non-standard sequences. In the absence of these design measures, a formal mission constraint should have been documented to restrict operational conditions to the limits of hardware qualification.

<u>Lessons Learned</u>: *Likely non-standard mission sequences should either be encompassed by design requirements or formally restrained by mission protocols. Formal documentation of mission constraints will not prevent the occurrence of non-standard operations, but it will ensure that violations of the requirement are recognized and considered in decision making.*

HEAO - PFR 2898. After 253 days in orbit, the High Energy Astronomical Observatory (HEAO) C-1 instrument experienced a rapid temperature rise in the primary detector and primary methane tank. The evidence indicated that the instrument had depleted its primary refrigerant (methane), requiring termination of the experiment after 8 months in orbit. The predicted life of the refrigerant was 330 days. The 6-month primary mission requirement was satisfied, but not the one-year extended mission.

The early depletion of the primary cryogen was attributable to an overestimate of (1) the methane tank fill quantity and (2) the primary stabilization effect. Another smaller reduction in lifespan may have been caused by an actual external operating temperature slightly higher than predicted; this was due to the occurrence of two "hot" galactic scan periods which were not included in the prediction. In addition, the estimated refrigerant shortfall may have been exaggerated due to false readings caused by a thermal short between the primary and secondary stages of the cryostat.

<u>Lessons Learned</u>: *Validate thermal models, or perform adequate thermal testing to provide realistic estimates of thermal performance.*

SME - PFR 54830. The backup grating drive motor in the Solar Mesospheric Explorer (SME) observatory module did not step to the commanded position for enabling ozone measurements. When the primary drive was engaged, the motor still would not step. Based on similar symptoms during pre-launch grating tests, it appeared that the grating was too cold to slip properly. This problem continued on subsequent orbit passes.

Investigation determined that this problem surfaced after temperature limits were installed into software. The corrective action involved updating the limits and the corresponding programmed responses.

Lessons Learned: Review and update thermal model. A capability for in-flight software modifications facilitates failure recovery. Develop an integrated product assurance approach for mechanisms.

WFPC - PFR 53932. In August 1990, the temperature indication for the Wide Field Planetary Camera (WFPC I) Camera 6 electronics furnished intermittent bad values. Once per minute, the indicated temperature toggled from an acceptable value of 11.4^0C to an unacceptable 49.2° C. Simultaneously, a WFPC error message was received which implied an error in primary RAM. This problem occurred continuously until it disappeared three hours later when a RAM memory dump was requested. A single toggle event occurred two days later.

No corrective action was implemented because the address location of the errors was not a critical area of RAM. The anomaly was reevaluated later to determine if it would impact WFPC II. It is unclear whether it was environmentally induced. It is possibly attributable to hardware degradation. Environmentally stressed thermal sensors and temperature monitoring circuitry have produced intermittent temperature readings on both NASA and U.S. Air Force craft. On

Magellan, for example, a combination of temperature cycling and solar array drive motor vibration caused erratic thermal sensor readings.[4]

Lessons Learned: Derive engineering guidelines for device mounting and stress relief commensurate with the mission and the ground and flight environments.

III. CONCLUSIONS/LESSONS LEARNED

Review of the JPL mission problem/failure records extending back to Viking shows that 20 percent of reported hardware anomalies may have been induced by factors related to the space environment. The statistical significance of this percentage is limited by the small size of the sample-- 16 out of a total of 82 incidents-- and accurate problem/failure analysis was hindered by an inability to recover the discrepant hardware. However, it is spaceflight that provides the most realistic test environment for validating the effectiveness of a product assurance program. NASA has devoted considerable resources to obtaining the most accurate picture of spacecraft performance possible, and these incidents reflect real hardware vulnerabilities experienced in an environment which can only be imperfectly duplicated on Earth.

The data analysis in Section II suggests that there are identifiable failure modes and trends across JPL programs, some of which may represent a risk to future unmanned missions. Analysis of environmentally-induced anomalies does not suggest a pattern of simple engineering oversights, but rather an evolving understanding of complex factors affecting hardware during extended interplanetary missions, and an understanding of appropriate measures to mitigate their impacts. The discipline of reliability engineering provides at least five areas of opportunity to improve future missions based on lessons learned on prior programs:

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[4] Oberhettinger, D.: Investigation of Thermal Sensor Failures Aboard Unmanned Spacecraft, Jet Propulsion Laboratory Document JPL D-11377, April 1994.

1. **Environmental Models**: Provide tools to accurately predict the space environment to be encountered on a given mission profile. Continually update environmental models for incorporation into mission design requirements.

2. **Environmental Requirements Specifications**: Specify the environmental parameters which each hardware subsystem must be designed to withstand, based on data from the models and on an up-to-date understanding of the mission profile, including reasonably probable off-nominal conditions. Consider opportunities for enhancing the rigor of requirements analysis for complex mechanical assemblies such as deployment mechanisms.

3. **Design Margins**: Design hardware to meet the environmental requirements specifications, with sufficient tolerance to minimize mission risk. Consider tradeoffs between reduced risk and higher cost.

4. **Environmental Test**: Perform ground tests to exercise the hardware functions under conditions similar to the post-launch environment, correct unacceptable design deficiencies, and retest. Where the former may be more cost-effective, a balance must be struck between (1) testing in configurations representative of flight and (2) reliability assessment by analysis.

5. **Mechanism Product Assurance**: Integrate the diverse elements of design, testing, and qualification of complex mechanisms into a systematic product assurance approach.

Table 1 identifies opportunities where improvements in one or more of the above four subdisciplines might have prevented or mitigated the anomalies described in Section II.

Table 1 shows that preventing most environmentally-induced anomalies would have required application of two or more of the five subdisciplines listed above. Of these, modeling and requirements specification are best aided by mission iterations-- the more missions completed, the more mature the understanding of the spaceflight environment. Environmental design of hardware is more of a moving target due to changes in materials, parts, and spacecraft design concepts, but reliability databases and design reviews provide opportunities to prevent repeating past errors. Subjecting hardware to both environmental testing and extensive analysis may be redundant; guidance is needed in optimizing test versus analysis decisions.

The Magellan mission to Venus is an example of the need to bolster the first four subdisciplines. It suffered data losses due to harsh thermal conditions which signified deficiencies in the **thermal model**, especially in definition of optical properties (PFRs 52226, 52227). Thermal **design margins** for the extended mission were consumed by the spacecraft's optical properties (PFR 52226) and by contamination of thermal control surfaces (PFRs 52228, 52240). Magellan thermal-vacuum **testing** provided inadequate duration bakeout to remove sources of thermal control surface contamination (PFRs 52228, 52240). All of these anomalies can be directly related to the particularly severe thermal environment of the Venus orbit mission profile; subsequent missions to the inner planets could reduce mission risk by incorporating appropriate product assurance improvements such as longer duration high temperature bakeout.

Table 1
Product Assurance Subdiscipline Correlations of JPL Environmental Anomalies

PFR NO. & BRIEF DESCRIPTION OF ANOMALY & CAUSE	ENVIRONMENTAL MODELING	REQUIREMENTS SPECIFICATION	DESIGN MARGINS	ENVIRONMENTAL TEST	MECHANISM PA
35409: loss of IRU: piece part short.				X	
35401: checksum glitch: launch dynamics/EMI.		X			
41009: CST degradation: part radiation tolerance.	X	X	X	X	
41014: LECP degradation: circuit power dissipation.		X	X	X	
41035: data loss from timing offset: ESD caused PORs.	X	X			
41026: IRIS signal degraded: mat'l radiation sensitivity.				X	
52240: bay overtemp.: degraded reflectance of OSRs.	X	X	X	X	
52228: OBC overtemp.: degraded reflectance of OSRs.	X	X	X	X	
52226: REM overtemp.: tail-to-sun s/c attitude.	X	X	X	X	
52227: SRM overtemp.: Erroneous modeling of flange.	X		X		
52235: AACS memory loss: electronic package design.			X		
52222: starcal failures: STU sensitivity to solar flares.	X	X			
52602: SSI noise spikes: radiation-induced noise.	X	X			
52603: NIMS cover stuck: thermal distortion of cover.			X		X
52615: PWS interference: bearing noise & motor EMI.				X	X
58332: Mag Boom indication: mechanism thermal design.			X	X	X
53831/55359: AST too cold: exposed to temp're extreme.		X			
2898: HEAO lost coolant: inaccurate temp're predictions.	X				
54830: SME drive froze: ill defined temperature limits.	X				X
53932: bad temperature values: thermal stress of parts.			X		

In addition, environmental design may have been a contributing factor in other incidents not identified as environmentally-induced. For example, an earlier report on mechanical anomalies discussed the Galileo high gain antenna, which accumulated environmental stresses from vibration testing, antenna rib preloading, four cross-country trips, post-launch ignition of the upper stage, and vibration in the vacuum environment.[5] As was shown there, it would have been difficult to define a ground test program to duplicate the exact operating conditions that the antenna deployment

[5] Oberhettinger, D.: Investigation of Mechanical Anomalies Affecting Interplanetary Spacecraft, Jet Propulsion Laboratory Document JPL D-11951, September 1994, pp. 13-14.

mechanism experienced in flight. Environmental conditions which varied from the test environment (such as vibration *and* vacuum *and* weightlessness, but occurring only *after* shock occurring *after* an extended period of ground storage) may have had a significant mission impact on Galileo. Since NASA does not consider it feasible to conduct vibration tests in a vacuum, such failure modes may require product assurance measures other than ground testing to prevent a reoccurrence. Galileo further illustrates the need for robust design practices and adequate design margin.

Another conclusion drawn from the analysis pertains to the physical design and fabrication of electronic assemblies. Reliability analysis, as it is performed by JPL, focuses on detailed examination and computer evaluation of circuit schematics to characterize power dissipation, check part derating, identify sneak circuits, and find other potential trouble spots. However, circuit analysis techniques generally do not consider features which do not appear on schematics.

As an example of this, when Magellan suffered a memory failure a few seconds after SRM separation, it was traced to a voltage transient through the spacecraft chassis (PFR 52235). Analysis showed that the AACS memory board was located sufficiently close to the ground plane for a one-volt transient to short to the chassis, probably over stressing a piece part and causing a memory failure. The preferred design solution would likely have been to suppress the transient and not to move the board; still, no review of circuit schematics could have disclosed this latent short-to-ground failure mode. This aspect of hardware design is the province of electronics packaging specialists: their design work also requires product assurance oversight.

Another example (which was not reviewed in Section II) was revealed by the Mars Observer investigation subsequent to loss of the spacecraft. Mars Observer used an inherited grounding approach which may have been inferior to the standard JPL grounding scheme. In addition, JPL Reliability Engineering discovered a single-point failure mode where two diodes were each insulated from the spacecraft power supply (EPS) chassis by a thin mica washer. A diode short to ground would cause a loss of spacecraft power. Tests showed that attachment of the diode usually resulted in over-torquing of the fastener, cracking the insulating washer. A circuit analyst studying only the circuit diagram would not even have considered this potential failure.

Today, relationships between packaging, geometry, and electrical performance are of even greater concern in electronics design. An integrated process is needed for combining analysis of mechanical and electrical failure modes.

Two other general conclusions follow from the review:

1. **Hardware redundancy is shown to have benefit in assuring spacecraft survival in extreme environments.** Incidents like the Viking IRU power loss (PFR 35409) and the Magellan AACS memory B inhibition (PFR 52235) point out the advantage of retaining redundancy of critical spacecraft functions where affordable. When a piece part or subassembly has design or manufacturing defects, environmental stress may trigger its failure, while a similar part in the backup unit may survive the stress. Similarly, if hardware performance is only degraded by environmental conditions, redundant capacity may aid in ensuring full data coverage. However, when a subsystem is inherently vulnerable to environmentally induced failure, it is unlikely that the backup(s) will fare any better than the primary unit. Most of the anomalies reviewed

involved hardware where backup was not feasible, such as spacecraft structures, the thermal subsystem, and scientific instruments.

2. **Ground control of spacecraft provides opportunities for implementing operational work-around solutions.** JPL has been adept at implementing ad hoc procedural measures to work around unanticipated in-flight problems. In 11 of the 15 environmentally-induced anomalies reviewed in this report, operational work-arounds were identified and successfully implemented by ground control. A failed automatic sequence can be commanded step-by-step by ground control, or a failed unit can be substituted by manually switching to backup. The reliability program planning process considers trade-offs in establishing required mission reliability: a higher level of risk may be taken in an equipment design if an opportunity exists for an in-flight fix. Charting opportunities to implement in-flight fixes is an appropriate task for inclusion in NASA's pre-flight risk mitigation planning process.

   However, the more recent NASA program initiatives indicate a trend toward greater spacecraft autonomy. Labor-intensive Mission Operations provides a target for budget cuts, while advances in computer power and miniaturization encourage passing greater control of spacecraft functions to on-board processors. The effectiveness of these controllers will be as good as the quality of their software and the comprehensiveness of the pre-defined diagnostic and corrective routines. NASA's long term plans to launch many small probes lacking uplink corrective action capability will mean that risk managers must build all the mission reliability into the hardware and software.

IV. RECOMMENDATIONS

The findings of this study support the need to examine additional product assurance and environmental engineering measures for the design of hardware subject to environmentally induced problems. Table 2 summarizes recommendations, following from study of JPL anomalies, for achieving reliability on future spacecraft and flight instruments. The following measures may be applicable to future NASA product assurance programs:

1. **Make incremental improvements in the accuracy of environmental models based on flight experience**. Additional empirical data obtained from new spaceflight missions permits the upgrading of theory-based environmental models to provide improved accuracy in mission planning. Since the anomalies reviewed in this report extend as far back as Viking, launched in 1975, additional iterations of space environment models have been performed. For example, the solar flare model has been updated, and ESD charging on spacecraft structures has been studied. The model of the proton environment has been readjusted based on Galileo experience.

   However, inadequacies in the Magellan thermal model point out the risks inherent in novel mission profiles and the need to collect further data as spacecraft encounter environmental extremes. None of the current thermal models, for example, simulate solar specular reflection. They are capable of predicting diffuse reflection, but neither the NEVADA nor TRASYS models are effective in evaluating reflections with high angular dependence on vectors (such

Table 2

Product Assurance Program Implications of JPL In-Flight Environmentally-Induced Anomalies

Sub-discip-line	Observations/Lessons Learned	Product Assurance Program Implications
ENVIRONMENTAL MODELS	• Observed environmental parameters during mission exceed predictions. • Inadequate thermal model, and resulting deficiencies in design and testing. • Transmitter powering or pyro firing can induce a state change.	• Make incremental improvements in the accuracy of environmental models based on flight experience. • Consider outgassing products when determining surface optical properties. • Include MGN experience in the optical properties database. • Perform instrumented system tests of NSI firing to investigate possible noise-induced failures.
ENVIRONMENTAL REQUIREMENTS SPECIFICATIONS	• Observed environmental parameters during mission exceed specifications. • Non-standard mission operations may subject hardware to stresses exceeding specifications. • Standard mission operations may subject hardware to stresses exceeding expectations. • Charging of external surface conducts ESD to s/c ground. • Diminished efficiency of the spacecraft thermal subsystem.	• Continuously tailor environmental specifications to flight experience. • Environmental specifications should accommodate reasonable non-standard sequences. • Inspect to confirm that anodic coatings are present, and verify the emittance of the coating. • Study outgassing and contamination of thermal control surfaces. • Consider vacuum bakeout of all organic adhesives.
DESIGN MARGINS	• Mission may subject single-channel hardware to environmental extremes. • Component or subassembly vulnerability to single-point failure or degradation from environmental stress. • Circuit analysis techniques are not effective in evaluating features which do not appear on schematics. • In-flight environmental changes are intentionally commanded by mission controllers without consultation. • Thermal cycling over stresses structure-mounted piece parts.	• Retain redundancy of critical functions. • Increase PA scrutiny of electronics packaging. • Improve communication between mission operations and hardware designers and peer reviewers; ensure enforcement of flight rules through special deployment reviews. • Develop guidelines for device mounting and stress relief.

Table 2 (Continued)

Product Assurance Program Implications of JPL In-Flight Environmentally-Induced Anomalies

Sub-discip-line	Observations/Lessons Learned	Product Assurance Program Implications
ENVIRONMENTAL TEST	• Thermal-vacuum test does not duplicate solar energy transfer in terms of reflection and shadowing. • Environmental extremes cause material degradation or outgassing and contamination of thermal control surfaces. • Anomalies occur during launch or during module separation. • Spin bearing and motor-induced noise interferes with instrument sensors.	• Perform adequate thermal testing to provide realistic estimates of thermal performance; verify thermal control design changes by test. • Conduct solar simulation testing at the subsystem level. • Improve test and characterization of materials. Address contamination concerns early in the hardware build cycle. • Review shock and vibration test sequence. • Analyze EMI test variances from the flight environment.
MECHANISM PRODUCT ASSURANCE	• Adequate thermal margins minimize mission risk. • Operations should obtain concurrence from designers before commanding environmental changes to the mission profile. • Contamination concerns should be addressed early in the hardware build cycle.	• Develop an improved product assurance approach to qualifying complex mechanisms and actuators. • Continue to schedule special deployment reviews as a flight rule enforcement tool. • Analyze ground test variances from the flight environment, e.g., mechanically induced noise.

as in the Magellan rocket engine nozzles). The SEU/TID radiation monitors flown on Clementine provided valuable additional data on radiation dose, high energy proton and heavy ion environments, and long-term exposure to solar micro-flares. NASA plans for the New Millennium program offer opportunities to devote flights exclusively to advanced technology demonstrations; instrumentation aboard these flights may offer additional opportunities to improve knowledge of space environmental conditions. A coordinated, sustained effort by NASA to maintain these environmental databases could provide significant benefits to lower cost/short development time flight projects.

2. **Develop improved tools for integrating thermal analysis with 3-D modeling of spacecraft structures.** Use of improved automated tools for integrating thermal analysis with three-dimensional modeling of spacecraft structures may be beneficial to NASA. Spacecraft geometry is an important factor in determining the thermal radiation interchange between surfaces. Modern simulation techniques allow rotation of virtual spacecraft structures through every attitude anticipated by mission specifications. It is recommended that any variation from the physical configuration baseline be carefully modeled for all spacecraft, including the smaller and more standardized spacecraft proposed in the new NASA initiative. The Project Design Center and the Flight System Testbed are new JPL facilities established to facilitate system-level evaluations of flight hardware. The Project Design Center will establish a capability for integrated modeling of complex systems, while the Flight System Testbed permits JPL to create a virtual spacecraft by connecting components and engineering models at different stages of development. These resources may offer cost effective opportunities to improve the rigor of engineering analyses.

3. **Evaluate potential for transient-induced state changes.** Incidents were described where transmitter powering (during Voyager) or NSI (NASA standard initiator) firing caused power transients and subsequent failures with potential for major mission impact. A better understanding of circuit vulnerability to transient signals may reduce the need to employ risky operational measures. Realistic, instrumented, system tests of NSI firing could be performed to investigate the potential for noise-induced failures.

4. **Create a NASA-wide database for tailoring environmental specifications to flight experience**. Environmental requirements specifications require periodic fine tuning to reflect the evolving understanding of the space environment and the impact of variations in mission profiles. Recently, for example, JPL readjusted the solar proton model based on Galileo experience. However, much of the data gathered by Earth-orbiters are not analyzed due to funding limitations, and analyzed data from NASA and military missions are not always widely disseminated. Improved coordination and information exchange between NASA centers, industry, and the Department of Defense would be cost effective.

   NASA-wide availability of valuable environmental data, such as JPL's experience with Magellan thermal degradation, would also improve the spacecraft design knowledge base. The change in solar absorptance for Magellan proved to be significantly greater than anticipated. The management of interagency data exchange may be further challenged by increased data flow resulting from the advent of frequent, short duration flights and improved flight systems performance sensors.

5. **Increase product assurance scrutiny of electronics packaging**. Circuit analysis techniques employ automated tools which draw upon schematic data to evaluate electrical incompatibilities and other circuit design defects. However, the circuit diagram is a representation of circuit electrical functions, and it has little similarity to the physical arrangement of the circuit board. Two piece parts that are incompatible because they are located in too close proximity on the printed circuit board, may nevertheless appear at opposite ends of a circuit diagram. Since there would be no incompatibility within the electrical circuit, this condition would not be detected by a failure mode and effects analysis (FMEA).

   Similarly, neither FMEA nor fault tree analysis (FTA) would detect board delamination nor inadequate strain relief on soldered leads because the analysis is performed on the drawings rather than on the hardware. The current product assurance practice is to use ad hoc measures to detect or preclude packaging problems. The measures may include generic qualification, problem avoidance sessions attended by reliability engineers, and "lessons learned" documentation. There is no systematic reliability review of the packaging engineer's work, and the circuit analyst may never actually see the hardware. Strengthening Reliability Engineering oversight into package design appears warranted. A process is needed for examining the actual hardware and identifying non-circuitry related problems and design life concerns. Due to the growing interdependency of packaging, geometry, and electrical performance, an integrated approach is required that combines analysis of mechanical and electrical failure modes for electronic assemblies.

6. **Develop guidelines for device mounting and stress relief**. The anomaly history shows a trend of problems with providing mechanical stress relief for small mechanical components. Vulnerable components may include ground straps, heat sinks, and piece parts mounted directly to spacecraft structures. Damage to thermal sensors, which may be mounted directly to high stress modules such as rocket engines, comprises the largest single group of in-flight failures in the JPL anomaly report database.

   Further study of temperature cycling is needed to derive engineering guidelines for stress relief commensurate with the mission and the anticipated environment. Development of a set of standard mounting procedures and configurations for failure prone devices would be useful. A description of measures for stress relief to avoid structural cracks and strains due to temperature and power on-off cycles may be a suitable candidate for a NASA Preferred Reliability Guideline.

7. **Provide margins for environmental specifications to accommodate reasonable non-standard sequences**. The in-flight anomaly record shows that mission operations may have subjected flight hardware to environmental conditions exceeding those anticipated from the flight profile. One example was a Shuttle-borne instrument which was chilled by extended exposure in the Shuttle's shadow. It is preferable that mission planners define operational sequence requirements which identify all likely modes of operation. Environmental specifications could then provide margins that accommodate reasonable departures from operational plans. Where such design flexibility is not feasible, it is recommended that a formal mission constraint be issued and documented to restrict the mission profile to the limits of hardware qualification.

8. **Improve communication between mission operations and hardware designers and peer reviewers**. The anomaly review records incidents where the mission profile was changed in-flight, resulting in variations from the expected spacecraft environment. Coming a long time after the original hardware design, seemingly minor operational changes have had significant mission impacts. For example, the decision by Mission Operations to leave the NIMS shield heater activated during cover deployment was implemented without consulting the hardware designers. Since then, a special review prior to every deployment has been instituted to prevent flight rule violations.

   This review of essential subsystems must extend down to the component level. The component engineer's cognizance typically ends with the receipt of a piece part which meets specifications based on the anticipated environment. The effect of changes to the mission environment may not be clear to the design engineer, who may have accepted the piece part without fully understanding the limitations on its application.

   This organizational problem may be mitigated by the new emphasis on shorter flight program life spans. With smaller program staff, the hardware designer and the operations engineer may even be the same person. Reduced mission objectives for single-purpose spacecraft will likely result in simpler system designs, providing greater visibility of operations-hardware interactions. Still, it has been evident that modifications are frequently not given the same level of scrutiny as the original design. When changes are made to plans for spacecraft storage and handling or to the mission profile, it would be useful to convene a peer review panel to review the impact of the changes on essential subsystems.

9. **Develop an integrated suite of miniaturized sensors with a single spacecraft data/command interface**. The anomaly record suggests that some spacecraft systems are developed with insufficient understanding of the space environmental hazards they must survive. These include both onboard hazards which are not amenable to ground test, such as EMI from motors and RTGs, and external factors such as radiation from solar flares and trapped planetary environments. Because it is not practical to "engineer out" many space-induced anomaly modes using existing technology, in-flight upsets and failures will continue to occur. Mission impacts may become more significant, especially as onboard systems are miniaturized to reduce power and weight, lower launch costs, and facilitate access to space. The interactions of spacecraft electronics with the space environment become increasingly important as components are downsized using hybridization technology.

   The NASA Technology Insertion program provides an opportunity to develop and fly a suite of protoflight, miniaturized, onboard diagnostic sensors to improve the characterization of hazardous space environmental conditions and their effects on advanced spacecraft components and systems. NASA would benefit from an integrated suite of miniaturized sensors, optimized for low weight, volume, power, and operational manpower. Sensor data would be recorded by a microprocessor-controlled central processing unit with a single spacecraft data/command interface to minimize the use of telemetry channels. The objectives of this technology insertion initiative would be to develop improved design guidelines and engineering criteria for use by spacecraft environmental design engineers, and to increase the availability of diagnostic data for autonomous onboard decisionmaking. Data on hazardous particle populations, associated in situ magnetic fields, and other environmental conditions would be collected for both research and diagnostic purposes.

10. **Institute enhanced product assurance measures for complex mechanisms and actuators**. The operation of complex mechanisms such as solar panel, boom, and antenna drives and instrument cover releases tends to be mission critical with no backup capability. They are more susceptible to catastrophic failure, lacking the graceful degradation often characteristic of electronic assemblies. The four environmentally induced mechanical anomalies identified in Table 1 support the conclusions of an earlier report that complex mechanisms may not receive the effective product assurance scrutiny typically applied to electronic design.[6]

    Unlike electronic assemblies, which make use of standardized packaging processes and interface characteristics, complex devices such as deployment actuators are more difficult to analyze because component properties and interactions are not easily defined. Also, the combination and sequence of in-flight operating conditions affecting mechanisms, such as shock followed by vibration in a vacuum during weightlessness, are difficult to duplicate in a ground test program. Among other product assurance improvements, the Mechanical Anomalies report recommends use of failure mechanisms analysis to highlight the underlying "physics of failure" issues that cause the failure modes identified in the fault tree or FMEA.

JPL is presently pursuing several initiatives to strengthen the reliability engineering disciplines discussed on pages 18-19. For evaluating design margins applicable to the next generation of spacecraft hardware, a research task has been proposed to address Risk vs. Requirements Tradeoffs. Also, work has commenced on a Defect Detection and Prevention research task to aid flight projects in optimizing the choice whether to conduct an engineering analysis or an environmental test. New media for communicating reliability engineering preferred practices, guidelines, and "lessons learned," such as the World Wide Web, are being explored.

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[6] Oberhettinger, D.: Investigation of Mechanical Anomalies Affecting Interplanetary Spacecraft, Jet Propulsion Laboratory Document JPL D-11951, September 1994.